LORENTZ SYMMETRY VIOLATION AND SUPERLUMINAL PARTICLES AT FUTURE COLLIDERS

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Abstract

If textbook Lorentz invariance is actually a property of the equations describing a sector of the excitations of vacuum above some critical distance scale, several sectors of matter with different critical speeds in vacuum can coexist and an absolute rest frame (the vacuum rest frame) may exist without contradicting the apparent Lorentz invariance felt by "ordinary" particles (particles with critical speed in vacuum equal to c , the speed of light). Sectorial Lorentz invariance, reflected by the fact that all particles of a given dynamical sector have the same critical speed in vacuum, will then be an expression of a fundamental sectorial symmetry (e.g. preonic grand unification or extended supersymmetry) protecting a parameter of the equations of motion. Furthermore, the sectorial Lorentz symmetry may be only a low-energy limit, in the same way as the relation ω (frequency) $= c_s$ (speed of sound) k (wave vector) holds for low-energy phonons in a crystal. In this context, phenomena such as the absence of Greisen-Zatsepin-Kuzmin cutoff and the stability of unstable particles at very high energy are basic properties of a wide class of noncausal models where local Lorentz invariance is broken introducing a fundamental length. Observable phenomena from Lorentz symmetry violation and superluminal sectors of matter are expected at very short wavelength scales, even if Lorentz symmetry violation remains invisible to standard low-energy tests. We discuss signatures of this new physics at LHC and at other possible future colliders.

1 Introduction

"The impossibility to disclose experimentally the absolute motion of the earth seems to be a general law of Nature"

H. Poincaré

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"Precisely Poincaré proposed investigating what could be done with the equations without altering their form. It was precisely his idea to pay attention to the symmetry properties of the laws of Physics"

R.P. Feynmann

"The interpretation of geometry advocated here cannot be directly applied to submolecular spaces... it might turn out that such an extrapolation is just as incorrect as an extension of the concept of temperature to particles of a solid of molecular dimensions"

A. Einstein

Is relativity the result of a symmetry of the laws of Nature (Poincaré, 1904), therefore necessarily broken at some deeper level (Einstein, late period), or does it reflect the existence of an absolute space-time geometry that matter cannot escape (Einstein, early papers on relativity)? Most textbooks teach "absolute" relativity (early Einstein papers) and ignore the possibility of a more flexible formulation (Poincaré, late Einstein thought) that we may call "relative" relativity (relativity is a symmetry of the laws of Nature expressed by the Lorentz group: whether this symmetry is exact or approximate must be checked experimentally at each new energy scale). Modern dynamical systems provide many examples where Lorentz symmetry (with a critical speed given by the properties of the system) is a scale-dependent property which fails at the fundamental distance scale of the system (e.g. a lattice spacing). In practical examples, the critical speed of the apparently relativistic dynamical system is often less than 10^{-5} c and "relativity", as felt by the dynamical system, would forbid particle propagation at the speed of light. Light would appear to such a system just like superluminal matter would appear to us. In this note, we would like to emphasize that high-energy physics has reached technical ability allowing for crucial tests of the nature of relativity combining experiments at the future machines with data from the highest-energy cosmic ray events.

Non-tachyonic superluminal particles (**superbradyons**) have been discussed in previous papers (Gonzalez-Mestres, 1996 , 1997a and 1997b) and other papers have been devoted to Lorentz symmetry violation (Gonzalez-Mestres, 1997c, 1997d and 1997e) as well as to its astrophysical consequences (Gonzalez-Mestres, 1997f and 1997g) and to its application to extended objects (Gonzalez-Mestres 1997h). These papers refer also to other work in the field, and are all submitted to the EPS-HEP97 Conference.

2 Superluminal particles

Conventional tests of special relativity are performed using low-energy phenomena. The highest momentum scale involved in nuclear magnetic resonance tests of special relativity is related to the energy of virtual photons exchanged, which does not exceede the electromagnetic energy scale $E_{em} \approx \alpha_{em}\ r^{-1} \approx 1\ MeV$, where α_{em} is the electromagnetic

constant and r the distance scale between two protons in a nucleus. However, the extrapolation between the 1 MeV scale and the $1 - 100\ TeV$ scale (energies to be covered by LHC and VLHC) may involve a very large number, making compatible low-energy results with the possible existence of superluminal particles above TeV scale.

Assume, for instance, that between $E \approx 1\ MeV$ and $E \approx 100\ TeV$ the mixing between an "ordinary" particle (i.e. with critical speed in vacuum equal to the speed of light c in the relativistic limit) of energy E_0 and a superluminal particle with mass m_i , critical speed $c_i \gg c$ and energy E_i is described in the vacuum rest frame by a non-diagonal term in the energy matrix of the form (Gonzalez-mestres, 1997c):

$$\epsilon \approx \epsilon_0\ p\ c_i\ \rho\ (p^2) \tag{1}$$

where p stands for momentum, ϵ_0 is a constant describing the strength of the mixing and $\rho\ (p^2) = p^2\ (p^2 + M^2\ c^2)^{-1}$ accounts for a threshold effect with $M\ c^2 \approx 100\ TeV$ due to dynamics. Then, the correction to the energy of the "ordinary" particle will be $\approx \epsilon^2\ (E_0 - E_i)^{-1}$ whereas the mixing angle will be $\approx \epsilon\ (E_0 - E_i)^{-1}$. Taking the rest energy of the superluminal particle to be $E_{i,rest} = m_i\ c_i^2 \approx 1\ TeV$, we get a mixing $\approx 0.5\ \epsilon_0$ at $p\ c = 100\ TeV$, $\approx 10^{-2}\ \epsilon_0$ at $p\ c = 10\ TeV$ and $\approx 10^{-4}\ \epsilon_0$ at $p\ c = 1\ TeV$. Such figures would clearly justify the search for superbradyons at LHC and VLHC ($E \approx 100\ TeV$ per beam) machines provided low-energy bounds do not force ϵ_0 to be too small. With the above figures, at $p\ c = 1\ MeV$ one would have a correction to the photon energy less than $\approx 10^{-32}\ \epsilon_0^2\ p\ c_i$ which, requiring the correction to the photon energy not to be larger than $\approx 10^{-20}$, would allow for large values of ϵ_0 if c_i is less than $\approx 10^{12}\ c$. In any case, a wide range of values of c_i and ϵ_0 can be explored.

More stringent bounds may come from corrections to the quark propagator at momenta $\approx 100\ MeV$. There, the correction to the quark energy would be bounded only by $\approx 10^{-24}\ \epsilon_0^2\ p\ c_i$ and requiring it to be less than $\approx 10^{-20}\ p\ c$ would be equivalent to $\epsilon_0 < 0.1$ for $c_i = 10^6\ c$. Obvioulsy, these estimates are rough and a detailed calculation of nuclear parameters using the deformed relativistic kinematics obtained from the mixing would be required. It must be noticed that the situation is fundamentally different from that contemplated in the $TH\epsilon\mu$ formalism and, in the present case, Lorentz invariance can remain unbroken in the low-momentum limit, as the deformation of relativistic kinematics for "ordinary" particles is momentum-dependent. Therefore, it may be a safe policy to explore all possible values of c_i and ϵ_0 at accelerators (including other possible parametrizations of ϵ) without trying to extrapolate bounds from nuclear magnetic resonance experiments.

The production of one or two (stable or unstable) superluminal particles in a high-energy accelerator experiment is potentially able to yield very well-defined signatures through the shape of decay products or "Cherenkov" radiation in vacuum events (spontaneous emission of "ordinary" particles). In the vacuum rest frame, a relativistic superluminal particle would have energy $E \simeq p\ c_i$, where $c_i \gg c$ is the critical speed of the particle. When decaying into "ordinary" particles with energies $E_\alpha \simeq p_\alpha\ c$ ($\alpha = 1, ..., N$)

for a N-particle decay product), the initial energy and momentum must split in such a way that very large momenta $p_\alpha \gg p$ are produced (in order to recover the total energy with "ordinary" particles) but compensate to give the total momentum p .This requires the shape of the event to be exceptionally isotropic, or with two jets back to back, or yielding several jets with the required small total momentum. Similar trends will arise in "Cherenkov-like" events, and remain observable in the laboratory frame. It must be noticed that, if the velocity of the laboratory with respect to the vacuum rest frame is $\approx 10^{-3}\ c$, the laboratory velocity of superluminal particles as measured by detectors (if ever feasible) would be $\approx 10^3\ c$ in most cases (Gonzalez-Mestres, 1997a). More details can be found in the papers quoted as references.

3 Lorentz symmetry violation

If Lorentz symmetry is broken at Planck scale or at some other similar fundamental length scale, it turns out (Gonzalez-Mestres, 1997d and subsequent papers) that such a phenomenon can manifest itself at the highest cosmic-ray energies, typically in events above $10^{17}\ eV$. If Lorentz symmetry violation in the particle propagator follows a p^2 law beween $10^{21}\ eV\ c^{-1}$ and $100\ MeV\ c^{-1}$, it can be ≈ 1 at the highest observed cosmic ray energies and $\approx 10^{-25}$ at $p\ c \approx 100\ MeV$. Furthermore, a ≈ 1 effect in particle propagators is not needed in order to get leading effects in data. It can be shown, for instance, that a $\approx 10^{-18}$ effect at $10^{17}\ eV$ would be enough to modify π^0 lifetime above this energy, as the term $m_\pi^2\ c^3\ (2\ p)^{-1}$ (m_π = pion mass) becomes smaller than $10^{-18}\ p\ c$ Then, as energy increases, the particle lifetime would become longer when measured in units of the standard relativistic Lorentz-dilated lifetime. It is even not impossible that such mechanisms occur at lower energies, but this may be prevented (Gonzalez-Mestres, 1997e) by the requirement that cosmic rays with energies below $\approx 3.10^{20}\ eV$ lose most of their energy in the atmosphere. Detailed calculations adapted to each specific model should be performed.

A particularly appealing scenario, in view of experimental tests, would be the one where Lorentz symmetry violation has full strength at Planck scale. Then, in most nonlocal models we expect (Gonzalez-Mestres, 1997d and 1997e) that the expression for energy in terms of momentum, in the limit $k\ a \ll 1$ (k = wave vector, a = fundamental distance scale), contain an extra term $\Delta\ E \simeq -\ \alpha\ (k\ a)^2\ p$ where $\alpha \approx 0.1 - 0.01$. Writing $\Delta\ E \simeq \Gamma\ (k)\ p$, we have $\Gamma\ (k) \simeq \Gamma_0\ k^2$ where $\Gamma_0 = -\ \alpha\ a^2$. Such a behaviour is not incompatible with a possible gravitational origin of the deformation, although gravity would not necessarily be a fundamental force at Planck scale and the graviton may be a composite object made (like all other gauge bosons and presently known matter fields) of more fundamental (perhaps superluminal) matter interacting at scales smaller than a (e.g. Gonzalez-Mestres, 1997d). String-like models using Planck scale may then describe composite objects made of superluminal matter.

Again, very high-energy accelerator experiments (especially with protons and nuclei)

can play a crucial role. Contrary to the previous case, they should now be performed in the very-forward region. At LHC, FELIX could provide a crucial check of special relativity by comparing its data with cosmic-ray data in the $\approx\ 10^{16}\ -\ 10^{17}\ eV$ region. VLHC experiments would be expected to lead to fundamental studies in the kinematical region which, according to special relativity, would be equivalent to the collisions of $\approx\ 10^{19}\ eV$ cosmic protons. With a 700 TeV per beam $p\ -\ p$ machine, it would be possible to compare the very-forward region of collisions with those of cosmic protons at energies up to $\approx 10^{21}\ eV$. Thus, it seems necessary that all very high-energy collider programs allow for an experiment able to cover secondary particles in the far-forward and far-backward regions. A model-independent way to test Lorentz symmetry between collider and cosmic-ray data sould be carefully elaborated, but the basic phenomena involved in the case of Lorentz symmetry violation can be (Gonzalez-Mestres, 1997d and 1997h):

i) failure of the standard parton model (in any version, even incorporating radiative corrections);

ii) failure of the relativistic formulae for Lorentz contraction and time dilation;

iii) longer than predicted lifetimes for some of the produced particles (e.g. the π^0).

The role of high-precision data from accelerators would then be crucial to establish the existence of such phenomena in the equivalent cosmic-ray events. In this way, it would in particular be possible to perform unique tests of special relativity involving possible violations coming from phenomena at some fundamental scale close to Planck scale, and even to determine the basic parameters of Lorentz symmetry violation (e.g. of deformed kinematics).

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